

Estimating Generalized Soil-water Characteristics from Texture¹

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ABSTRACT

Soil-water potential and hydraulic conductivity relationships with soil-water content are needed for many plant and soil-water studies. Measurement of these relationships is costly, difficult, and often impractical. For many purposes, general estimates based on more readily available information such as soil texture are sufficient. Recent studies have developed statistical correlations between soil texture and selected soil potentials using a large data base, and also between selected soil textures and hydraulic conductivity. The objective of this study was to extend these results by providing mathematical equations for continuous estimates over broad ranges of soil texture, water potentials, and hydraulic conductivities. Results from the recent statistical analyses were used to calculate water potentials for a wide range of soil textures, then these were fit by multivariate analyses to provide continuous potential estimates for

all inclusive textures. Similarly, equations were developed for unsaturated hydraulic conductivities for all inclusive textures. While the developed equations only represent a statistical estimate and only the textural influence, they provide quite useful estimates for many usual soil-water cases. The equations provide excellent computational efficiency for model applications and the textures can be used as calibration parameters where field or laboratory soil water characteristic data are available. Predicted values were successfully compared with several independent measurements of soil-water potential.

Additional Index Words: soil-water potential, hydraulic conductivity, unsaturated moisture equations.

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RELATIONSHIPS OF SOIL-WATER POTENTIAL and hydraulic conductivity with soil-water content are necessary for many soil-water related investigations such as water conservation, irrigation scheduling, drainage, solute migration, plant growth, and plant-

Table 1. Summary of coefficients for linear regression Eq. [4] by Rawls et al. (1982).

Tension (kPa)	Intercept (a)	% Sand (b)	% Silt (c)	% Clay (d)	% Organic matter (e)	Correlation coeff. (R)
10	0.4118	-0.0030		0.0023	0.0317	0.81
20	0.3121	-0.0024		0.0032	0.0314	0.86
33	0.2576	-0.0020		0.0036	0.0299	0.87
60	0.2065	-0.0016		0.0040	0.0275	0.87
100	0.0349		0.0014	0.0055	0.0251	0.87
200	0.0281		0.0011	0.0054	0.0220	0.86
400	0.0238		0.0008	0.0052	0.0190	0.84
700	0.0216		0.0006	0.0050	0.0167	0.81
1000	0.0205		0.0005	0.0049	0.0154	0.81
1500	0.0260			0.0050	0.0158	0.80

water stress. These investigations commonly require soil-water potential and hydraulic conductivity for the computations of soil-water storage or soil-water flow.

Soil-water potential and hydraulic conductivity vary widely and nonlinearly with water content for different soil textures. Moreover, these relationships are relatively difficult and expensive to measure or are not feasible for short-term or remote investigations. Experience has shown that soil texture predominately determines the water-holding characteristics of most agricultural soils. Textural information is often either available or can be estimated by simple methods (Bouyoucos, 1951) and could readily serve as the principal input variable to a mathematical method for estimating soil-water characteristic relationships.

For many numerical models, measured data at selected values are often used in tabular form with interpolation. Equational representation of these relationships over the necessary ranges of soil-water content and soil texture would greatly reduce input data requirements, computer storage space, and execution time of mathematical models. It would be highly beneficial to have a computationally efficient method to estimate soil-water characteristics with reasonable accuracy from readily available inputs. The objective of this study was to develop such a procedure from results of previous statistical analyses of a large data base.

SOIL-WATER POTENTIAL

The relationship between soil-water potential and water content has been described in several ways. Brooks and Corey (1964) fitted the equation

$$\Psi = \Psi_c [(\theta - \theta_r)/(\theta_s - \theta_r)]^B \quad [1]$$

to the soil-water potential curves where Ψ is soil-water potential (kPa), Ψ_c is soil-water potential at air entry (kPa), θ is soil-water content (m^3/m^3), θ_s is saturation soil-water content (m^3/m^3), θ_r is residual soil-water content (m^3/m^3), which is an empirical value to straighten curved data on a log-log scale, and B is a fitted value. Equation [1] can be simplified to the form

$$\Psi = A \theta^B \quad [2]$$

by setting $\theta_r = 0$ and $A = \Psi_c \theta_s^{-B}$. This equational form has been supported by several recent studies (Campbell, 1974; Clapp and Hornberger, 1978; Gardner et al., 1970a,b; Rogowski, 1971; Williams et al., 1983; McCuen et al., 1981).

Arya and Paris (1981) presented a model to predict the soil-water tension curve from particle size distribution and bulk density data. Their model calculates a pore size distribution from particle size distribution, bulk density, and particle density. Then the pore radii are converted to equivalent soil-water tensions using the equation of capillarity at the corresponding volumetric water content.

Gupta and Larson (1979) used multiple linear regression equations of the form

$$\theta_p = a (\% \text{ sand}) + b (\% \text{ silt}) + c (\% \text{ clay}) + d$$

$$+ e (\% \text{ organic matter}) + f (\text{bulk density, Mg/m}^3) \quad [3]$$

to predict the soil-water content (θ_p , m^3/m^3) for 12 given soil-water potentials where a , b , c , d , and e are regression coefficients. Intermediate values could be linearly interpolated between the calculated points.

Rawls et al. (1982) also reported a multiple linear regression analysis of soil-water content at 12 soil-water potentials with soil attributes using a very extensive data set (2541 soil horizons with a wide range of each correlated variable). They used three linear regression equations of which the simplest is

$$\theta_p = a + b (\% \text{ sand}) + c (\% \text{ silt}) + d (\% \text{ clay})$$

$$+ e (\% \text{ organic matter}) + f (\text{bulk density, Mg/m}^3) \quad [4]$$

where a , b , c , d , e , and f are regression coefficients and textures defined by the USDA system. The other two regression equations included: (i) the addition of 1500 kPa water retention to those variables of Eq. [4], and (ii) the addition of both 33 and 1500 kPa water retention as correlated variables. Equations and coefficients containing the 33 and 1500 kPa moisture values were not further considered here since these data are often not readily available or obtainable. Only one or two of the three coefficients b , c , and d were simultaneously considered because of their dependency.

Using step-wise regression, Rawls et al. (1982) correlated only the most statistically significant variables in Eq. [4]. These coefficients are summarized in Table 1 for selected measured potentials from 10 to 1500 kPa. Some coefficients are zero showing insignificant effects; for example, at potentials of 10 kPa and greater, bulk density did not effect water content, which is consistent with other literature (Borg, 1982).

The equations have a small sensitivity to organic matter, as can be seen from the coefficients of Table 1. A 1% increase in organic matter caused a 3.2 and 1.5% by volume increase in moisture content at 10 and 1500 kPa, respectively. Organic matter has a very small range (0–3%) for most agricultural soils.

Soil texture, defined by the USDA system where sand = 2.0 to 0.05 mm, silt = 0.05 to 0.002 mm, and clay < 0.002 mm, is the dominant factor in the soil-water potential–content relationship. Clay content is the most important texture factor as seen by the coefficients in Table 1. Cosby et al. (1984) also clearly demonstrated that soil texture could be related to hydraulic characteristics when they applied regression and discriminant analysis to these and other data.

The results of Eq. [4] with the coefficients of Table 1 represent a valuable summary of an extensive data set. For ready application to soil-water computations, however, these water content values at selected potentials must be interpolated over the whole of the useful moisture range in a nonlinear fashion. To be computationally efficient and accurate, equations are needed; thus we conducted the subsequent analysis.

To select the equational forms, it is known that potential curves cannot be represented from saturation to wilting point by a straight line on log-log axes or any other first- or second-order equation because of the double inflection in the curve. However, at potentials greater than about 10 kPa, a log-log equation provides a reasonable estimate. A linear relationship is a good approximation from 10 kPa to air entry potential. At air entry potential and less, the soil is essentially

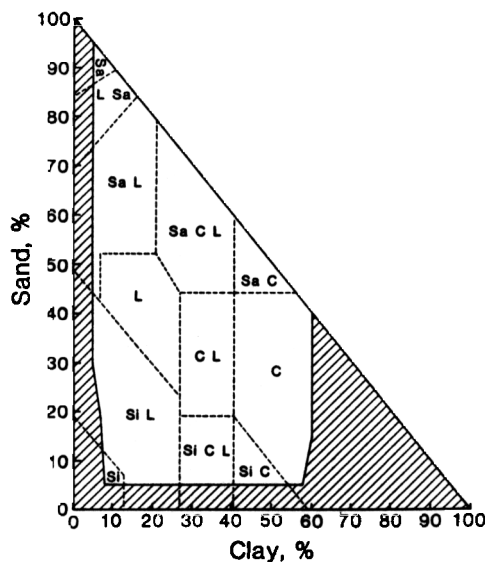


Fig. 1. Applicable textural region (clear) for the derived equations.

at saturation moisture content and the water content changes very little; thus a constant water content value is reasonable. Therefore, the complete water potential–water content curve can be represented by three equations for the ranges of (i) saturation to air entry, constant; (ii) air entry to 10 kPa, linear; and (iii) 10 to 1500 kPa and greater, curvilinear by Eq. [2].

For the range >10 kPa, we used Rawls' regression equations with an average organic matter content of 0.66% to generate moisture content values θ (m^3/m^3) for a systematic variation of textures for the 10 potentials Ψ (kPa) shown in Table 1. The soil texture triangle was divided into grids of 10% sand and 10% clay content increments. The 55 grid midpoints were used to generate the moisture contents for the 10 potential values from 10 to 1500 kPa. Of the 55 sets of values this produced, values were omitted for textures with >60% clay content, <5% sand, and <5% clay, because they exceeded the range of all but a few of the original data used in the statistical analyses by Rawls et al. (1982). The remaining 44 sets of values were correlated with Eq. [2] as the model.

The 44 A and B coefficients were separately correlated with sand and clay (USDA classification) content using stepwise multiple nonlinear regression techniques. The resulting

Table 2. Summary of derived soil-water characteristic equations.

Applied tension range, kPa	Equation
>1500 to 10	$\Psi = A \theta^B$ $A = \exp[a + b (\%C) + c (\%S)^2 + d (\%S)(\%C)]$ 100.0 $B = e + f (\%C)^2 + g (\%S)^2 + h (\%S)(\%C)$
10 to Ψ_e	$\Psi = 10.0 - (\theta - \theta_{10})(10.0 - \Psi_e)/(\theta_s - \theta_{10})$ $\theta_{10} = \exp[(2.302 - \ln A)/B]$ $\Psi_e = 100.0 [m + n (\theta_s)]$ $\theta_s = h + j (\%S) + k \log_{10} (\%C)$ $\theta = \theta_s$
Ψ_e to 0.0	$K = 2.778 \times 10^{-8} \{ \exp[p + q (\%S) + r + t (\%S) + u (\%C) + v (\%C)^2](1/\theta) \}$
Coefficients	
$a = -4.396$	$g = -3.484 \times 10^{-5}$ $p = 12.012$
$b = -0.0715$	$h = 0.332$ $q = -7.55 \times 10^{-2}$
$c = -4.880 \times 10^{-4}$	$j = -7.251 \times 10^{-4}$ $r = -3.8950$
$d = -4.285 \times 10^{-5}$	$k = 0.1276$ $t = 3.671 \times 10^{-2}$
$e = -3.140$	$m = -0.108$ $u = -0.1103$
$f = -2.22 \times 10^{-3}$	$n = 0.341$ $v = 8.7546 \times 10^{-4}$
Definitions	
Ψ = water potential, kPa	θ_{10} = water content at 10 kPa, m^3/m^3
Ψ_e = water potential at air entry, kPa	K = water conductivity, m/s
θ = water content, m^3/m^3	$(\%S)$ = percent sand (e.g., 40.0)
θ_s = water content at saturation, m^3/m^3	$(\%C)$ = percent clay (e.g., 30.0)

equation for A ($n = 44$, $R^2 = 0.99$) was

$$A = \exp [-4.396 - 0.0715 (\% \text{ clay}) - 4.880 \times 10^{-4} (\% \text{ sand})^2 - 4.285 \times 10^{-5} (\% \text{ sand})^2 (\% \text{ clay})] 100.0 \quad [5]$$

and that representing B ($n = 44$, $R^2 = 0.99$) was

$$B = -3.140 - 0.00222 (\% \text{ clay})^2 - 3.484 \times 10^{-5} (\% \text{ sand})^2 (\% \text{ clay}). \quad [6]$$

The value of 100.0 was included in Eq. [5] to convert from the original data units of bars to kilopascals. Thus, the potential–moisture content relationship of Eq. [2] for all potentials > 10 kPa can be estimated by soil texture with a

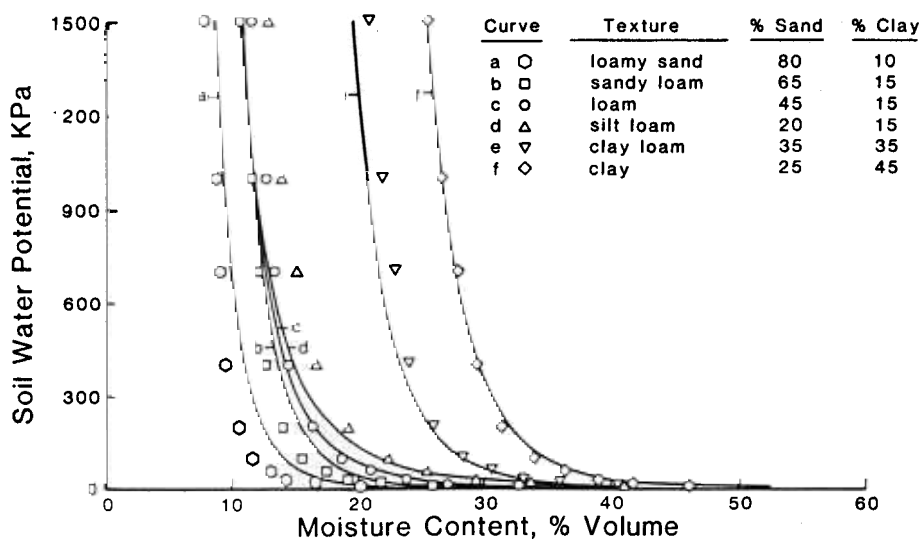


Fig. 2. Comparison of results from the derived equations with those from correlations by Rawls et al. (1982).

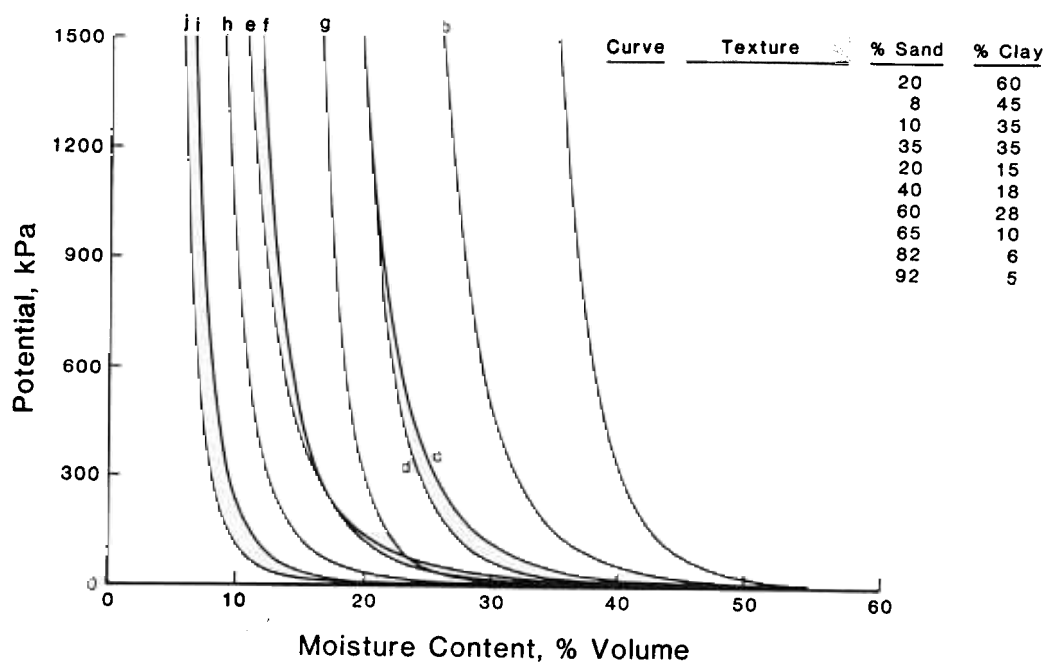


Fig. 3. Predicted potential curves for soil class centroid texture (0-1500 kPa range).

basis of the same 2500 samples correlated by Rawls et al. (1982).

For potentials <10 kPa, we first correlated saturation moisture content and air entry tension to soil texture. Using the saturation moisture contents reported by numerous literature sources and summarized by Strait et al. (1979) for 10 soil texture classes, we obtained the following regression equation:

$$\theta_s = 0.332 - 7.251 \times 10^{-4} (\% \text{ sand}) + 0.1276 \log_{10} (\% \text{ clay}) \quad [7]$$

where θ_s is moisture content at saturation (m^3/m^3), ($n = 10$, $R^2 = 0.99$). Air entry tension was then correlated to

saturation moisture content using reported air entry potential values for 10 texture classes reported by Rawls et al. (1982) resulting in

$$\Psi_e = 100.0 [-0.108 + 0.341 (\theta_s)] \quad [8]$$

where Ψ_e is air entry potential (kPa) ($n = 10$, $R^2 = 0.94$).

Having estimated θ_s from soil texture data, Ψ_e from θ_s , and Ψ at 10 kPa from Eq. [2], the 10 kPa to Ψ_e linear segment and Ψ_e to 0.0 kPa constant segment can be defined to complete the low tension portion of the potential-moisture relationship. Thus the complete characteristic curve may be estimated from soil texture data.

The combined equation set ([2], [5], [6], [7], and [8]) was tested over the range of the texture triangle to determine any

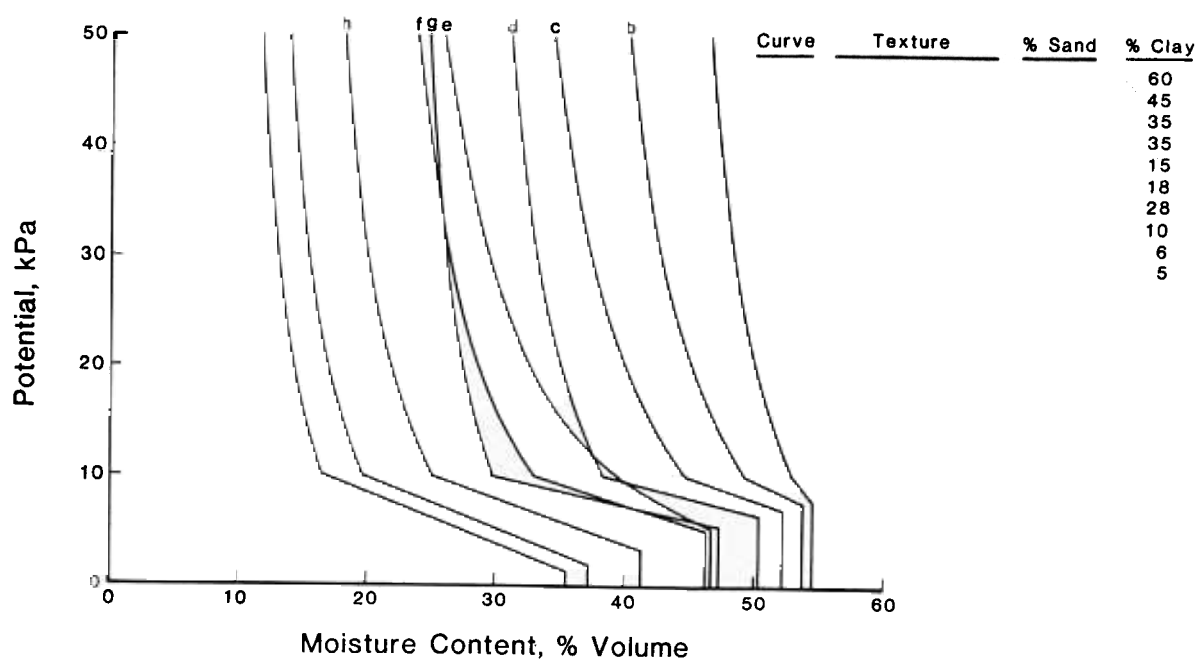


Fig. 4. Predicted potential curves for soil class centroid texture (0-50 kPa range).

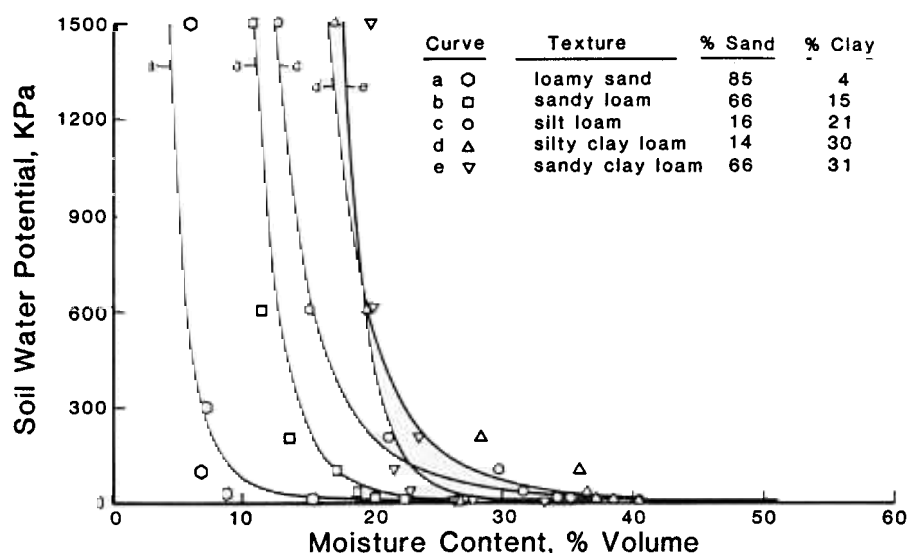


Fig. 5. Comparison of predicted equations with independent measured data.

areas of unreasonable result. At some low and high clay contents, the equations produced low potential moisture contents that exceeded the saturation moisture content. Figure 1 shows the region within the texture triangle for which the equations appear quite valid and is approximately defined as

$$5\% \leq \% \text{ sand} \leq 30\% \text{ with } 8 \leq \% \text{ clay} \leq 58\%, \text{ and} \\ 30\% \leq \% \text{ sand} \leq 95\% \text{ with } 5\% \leq \% \text{ clay} \leq 60\%.$$

Figure 2 shows some example comparisons of results from the equation set with those of Eq. [4], which was used to derive the equations. The degree of agreement is generally good over the wide range of soil textures. These examples show that a statistical comparison with the original data used to derive Eq. [4] would have produced a slightly reduced level of correlation than reported by Rawls et al. (1982), but the lack of uniform methods and textural definitions in these data made such an analyses of limited value.

The three curves, b, c, and d, in Fig. 2 show the sensitivity to change in sand content; while the three curves, d, e, and f, largely show the greater sensitivity to clay content. Figures 3 and 4 show predicted high and low ranges of potential curves for the centroid textures of soil classes using the derived equation set as summarized in Table 2. Shifts of texture away from the centroid values but remaining within the texture classes of Fig. 1 show that significant potential changes can result even for soils with the same general textural classification.

Independent sources of measured potential-soil-water content data with associated texture data (Arya et al., 1982; Williams et al., 1983; D. Miller, 1984, personal communication) were also used to verify Eq. [2], [5], and [6]. The comparisons shown in Fig. 5 illustrate that a generally good estimate was obtained using the derived equations. Some water potential measurement error, especially for the sandy clay loam soil, may well be present.

The worth of the derived equation set is to approximate

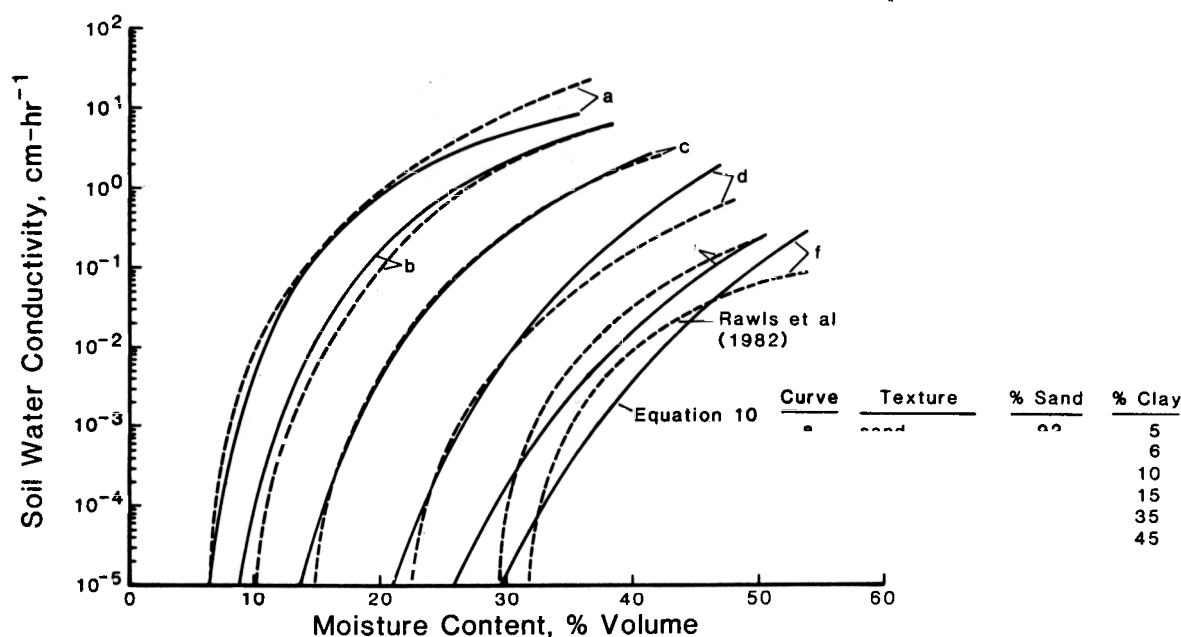


Fig. 6. Comparison of unsaturated hydraulic conductivity results from Eq. [10] with original curves from Rawls et al. (1982). (Multiply cm/h by 2.778×10^{-6} to obtain m/s.)

the full moisture range of the potential characteristic with minimal input data. While the derived relationships depend only on texture, other factors such as bulk density, structure, organic matter, clay type, and hysteresis may all have a secondary impact (Williams et al., 1983). Thus it is expected that the results from the derived equation set will only be an estimate, albeit a quite reasonable one, based on the large underlying data set. Should some field or laboratory data be available, it would be quite reasonable to moderately shift inputted textures (principally clay content due to its strong sensitivity) to cause appropriate matching.

HYDRAULIC CONDUCTIVITY

Early models to predict soil-water conductivity were either empirical or theoretical relationships with soil particle size or porosity. These models were usually based on conductivity at saturation and not readily applied to unsaturated conditions. Later models related unsaturated conductivity to moisture content or potential such as Campbell (1974), who used a form of

$$K = a\theta^b \quad [9]$$

where K is unsaturated conductivity (m s^{-1}), θ is moisture content (m^3/m^3), b is a function of B in Eq. [2], and a is a function of saturation moisture content. These models usually require calibration using measured data, although Bloemen (1980) developed reasonable relationships using soil texture and pore size distribution index.

Rawls et al. (1982) reported hydraulic conductivity curves for 10 texture classes that were averages of numerous reported curves. These hydraulic conductivity data did not correlate well with an equation of the form of Eq. [9]. Multiple nonlinear regression techniques were applied to these 10 curves using moisture content, percent sand, and percent clay as the independent variables. We derived the following equation for hydraulic conductivity using 230 selected data points uniformly spaced on the 10 curves ($n = 230$, $R^2 = 0.95$).

$$K = 2.778 \times 10^{-6} \{ \exp [12.012 - 0.0755 (\% \text{ sand}) + [-3.8950 + 0.03671 (\% \text{ sand}) - 0.1103 (\% \text{ clay}) + 8.7546 \times 10^{-4} (\% \text{ clay})^2] (1/\theta) \} \quad [10]$$

Equation [10] was found to provide quite reasonable values over at least the same textural range as those for water potential. Figure 6 shows hydraulic conductivity curves calculated using Eq. [10] for the centroid class textures and the curves (in the original units) from which the data were obtained (Rawls et al., 1982). For the extreme condition of near saturation or very dry and very high clay contents, the calculated values do not match reported values as well as desired; however, it is a good fit for a single equation over a large range of commonly encountered textures. Some adjustments may be appropriate for near saturation values for high clay content soils. Just as for potentials, other soil attributes than texture could well cause some deviations from the estimates by Eq. [10].

CONCLUSIONS

This study examined previous methods for estimating the relationships of soil-water content to potential and hydraulic conductivity. Using the results of previous broad-based correlations, equations were derived to estimate continuous relationships of soil-water moisture content to potentials and hydraulic conductivity from soil textures. The potential rela-

tionship is continuous and nonlinear from 10 to 1500 kPa, linear from 10 kPa to air entry potential, and a constant water content below air entry potential. The hydraulic conductivity relationship is continuous and nonlinear from saturation moisture content to near air dry. A complete summary of the derived equations and coefficients is provided in Table 2.

The equations are valid for a wide range of textures. They are computationally efficient to allow easy use with a digital computer and they provide reasonably accurate estimates of the unsaturated potentials and hydraulic conductivities with a minimum of readily available data. Comparisons with independent measured soil-water characteristic curves verified these results. Textural ranges within generally defined texture classes can cause significant changes of potentials and hydraulic conductivities. The estimated curves should be adjusted for effects of organic matter, clay type, density, structure, etc., to represent measured values or hysteresis by slight adjustments of the texture (clay primarily) when these secondary effects can be defined.

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